

Relative Group Delay Measurements with 0.3 ps Resolution: Toward 40 Gbit/s Component Metrology

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Abstract: We demonstrate relative group delay measurements on molecular absorption lines using a modulation phase shift technique yielding 0.3 ps resolution. Measured features as small as ~1 ps are shown to agree well with theory.

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Introduction

Future dense wavelength division multiplexing systems operating at 40 Gbit/s pose a number of formidable metrology challenges. Among the phenomena requiring high-resolution characterization is chromatic dispersion, which broadens optical data pulses through the wavelength-dependent refractive index variation of system elements. At higher data rates, characterization of relative group delay (RGD) due to chromatic dispersion in components becomes critical to system throughput. In optical fibers, broadband descriptions of the chromatic dispersion are sufficient. However, it is more challenging to characterize optical components such as narrow-band filters for 40 Gbit/s data rates, since these systems may need sub-picosecond RGD resolution in bandwidths on the order of tens of picometers. To help meet this industry challenge, the National Institute of Standards and Technology (NIST) has developed an RGD measurement technique targeted for 40 Gbit/s component metrology. Our technique relies on refinements to the established modulation phase shift method for measuring RGD [1], yielding enhanced phase stability over the time interval of the measurement. Given the many sources of absolute uncertainty in this measurement, the development of a calibration artifact with a theoretically predictable group delay is critical to the success of optical component measurements [2]. We present experimental and theoretical results for the measurement of RGD of molecular gas absorption lines, which have the potential to be stable and well-characterized standards.

Experimental Apparatus

Figure 1 shows the experimental apparatus we constructed for measuring group delay. We used an extended-cavity diode laser having an 80 nm tuning range centered at 1560 nm, with a single-mode linewidth of ~5 MHz in a

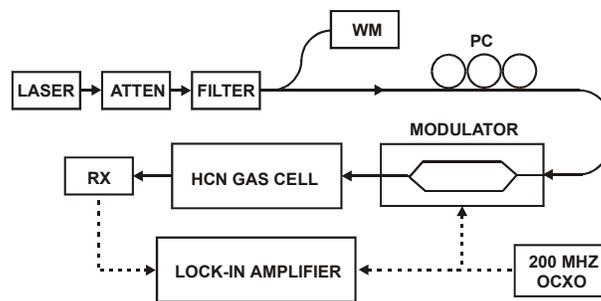


Figure 1. Experimental apparatus for measuring group delay on absorption lines in hydrogen cyanide gas. Solid paths represent optical fiber; dashed paths represent electrical connections. WM, wavelength meter; RX, photoreceiver; PC, polarization controller; OCXO, oven-controlled crystal oscillator.

one-second time interval. The laser light was passed through a variable optical attenuator and a narrow-band tracking filter. A small portion of the light from the filter was directed to a wavelength meter having sub-picometer resolution and accuracy. The remaining light was amplitude-modulated by a Mach-Zehnder modulator driven

electrically by an oven-controlled crystal oscillator (OCXO) at 200 MHz. The amplitude-modulated signal was passed three times through a gas cell containing hydrogen cyanide ($H^{13}C^{14}N$) gas at a pressure of 13 kPa (100 Torr). The total optical path through the gas was 22.5 cm. An AC-coupled photoreceiver was used to detect the modulated optical signal after the gas cell. The electrical amplitude and phase of the receiver signal were measured with a lock-in amplifier referenced to the OCXO. During a group delay measurement, the laser's wavelength was swept while the phase of the modulated signal from the receiver was recorded. Observed changes in arrival phase represent variations in the propagation time (group delay) through the device (360 ° of phase represents one period at the modulation frequency).

To achieve measurements with the highest resolution and lowest uncertainty, the exact method of data collection is critically important. The variable attenuator was necessary to counteract the power dependence of phase caused by electrical devices such as the photoreceiver, amplifiers, and lock-in amplifier. This was especially important when conducting measurements at the edge of a filter pass-band or at the center of a molecular absorption line. The tracking filter was used to remove amplified spontaneous emission noise from the laser, which we have observed to cause phase errors in some circumstances. Temporal drift of the phase during a measurement can be particularly debilitating because it is indistinguishable from the RGD structure of an optical component. The effects of system drift were removed by normalizing each value of phase to a subsequent reference phase measured at a fixed wavelength. Variations in phase at this fixed position represent the phase drift of the system, and recording its value in real time helps to remove phase drift from the RGD measurement. However, the reference phase must be measured at a wavelength position having both sufficient transmitted power and small chromatic dispersion. If the chromatic dispersion at the reference wavelength is too large, variability in tuning to the reference wavelength will translate into errors in the reference phase. We also minimized system phase drift by using a modulator that was designed to operate at quadrature without a DC electrical bias, which tends to drift with time. The residual (background) dispersion in the fiber leads of the system was removed from the absorption cell measurements by subtracting the RGD curve measured without the cell in place.

Theoretical Development

The theoretical motivation for using a molecular absorption line as a calibration reference is provided by the Kramers-Kronig relation [3], which enables the relative group delay $\tau(\lambda)$ to be predicted from a normalized transmittance profile $P(\lambda)$. We begin by defining the imaginary dielectric constant $K_i(\lambda)$ for a weak gas,

$$K_i(\lambda) = -\frac{\lambda}{\pi} \ln P(\lambda). \quad (1)$$

The Kramers-Kronig relations can then be used to calculate the corresponding real dielectric constant $K_r(\lambda)$,

$$K_r(\lambda) = \frac{2}{\pi} \int_0^{\infty} \frac{K_i(\lambda') d\lambda'}{\lambda'^3 [(1/\lambda'^2) - (1/\lambda^2)]} + 1. \quad (2)$$

Using the expressions for $K_i(\lambda)$ and $K_r(\lambda)$ the refractive index profile can be expressed as

$$n(\lambda) = \sqrt{(1/2)[K_r(\lambda) + \sqrt{K_r^2(\lambda) + K_i^2(\lambda)}]}. \quad (3)$$

Finally, by differentiation of $n(\lambda)$ the relative group delay $\tau(\lambda)$ can be calculated from

$$\tau(\lambda) = \frac{-\lambda}{c} \frac{dn(\lambda)}{d\lambda}, \quad (4)$$

where c is the speed of light in vacuum. If these expressions are evaluated numerically, arbitrary profiles of measured spectra can be treated without assuming a functional form for the normalized transmittance. Some signal processing may be necessary to remove high-frequency noise originating from the spectral measurement.

Measurement Results

$H^{13}C^{14}N$ has about 50 strong absorption lines in the 1530-1560 nm region and a number of weaker lines [4]. Figure 2 shows our measurement of the RGD across line P(16), recorded with wavelength steps as small as 3 pm. The inset

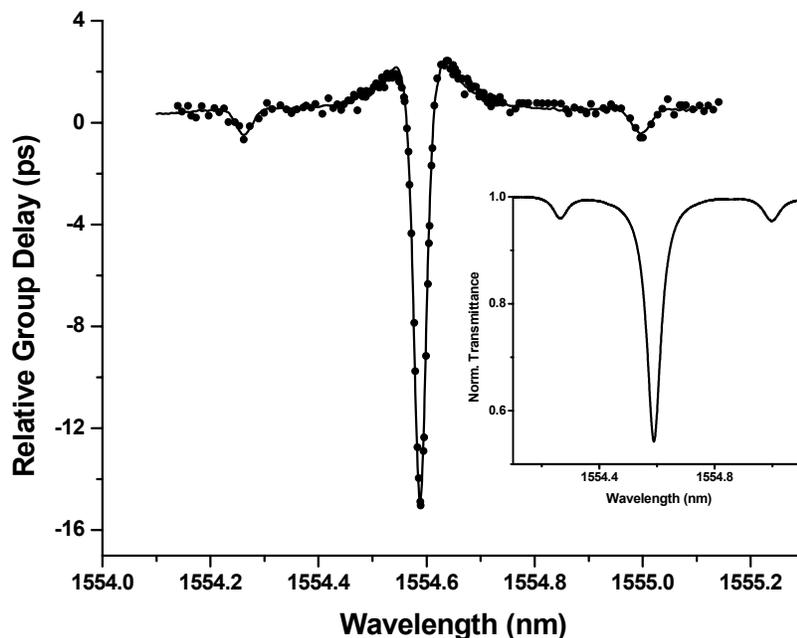


Figure 2. Measured relative group delay for line P(16) of hydrogen cyanide (shown by dots) along with a theoretical prediction (solid line). The reference phase was measured at 1554.1 nm. The prediction was calculated from the measured normalized transmittance of the line, shown in the inset.

to the plot shows the normalized transmittance profile we measured for line P(16), which is centered at 1554.589 nm with an absorption depth of about 45 %. Both the RGD and the transmittance plots show two weak absorption lines on either side of line P(16). The main plot of Figure 2 also shows a predicted RGD curve that was calculated by applying equations (1) through (4) to the measured transmittance. Aside from the removal of a measured background from the RGD measurement and the filtering of high-frequency noise from the calculation, no adjustments between the curves were made. The calculated curve and the measurement show good agreement, particularly in the magnitude of the RGD at the center of the P(16) line, and good measured resolution of the ~1 picosecond weaker features. The standard deviation between the curve and measured RGD is less than 0.3 ps, showing the potential for metrology of 40 Gbits/s components. The spectral position for measuring the reference phase was set to the beginning of the wavelength scale at 1554.1 nm. Without phase referencing, measurements of the absorption line had drifts of almost 2 picoseconds over intervals of 0.1 nm or more. The results presented in Figure 2 show a significant reduction in long-term drift, in turn decreasing the standard deviation in RGD by a factor of two. However, because extra time was required to perform the phase referencing, more short-term drift between adjacent measurement points was observed. We are investigating schemes to increase the short-term stability, and have been making comparisons with RGD measurements acquired by a low-coherence interferometric technique [5].

References

1. S. E. Mechels, J. B. Schlager, and D. L. Franzen, "Accurate measurements of the zero-dispersion wavelength in optical fibers," *Journal of Research of the National Institute of Standards and Technology* **102**, 333-347 (1997).
2. A. Motamedi, B. Szafraniec, P. Robrish, and D. Baney, "Group delay reference artifact based on molecular gas absorption," in *OFC Techn. Digest Series*, 2001, ThC8.
3. J. R. Reitz, F. J. Milford, and R. W. Christy, *Foundations of electromagnetic theory*, (Addison-Wesley Publishing Company, Reading, MA, 1980).
4. H. Sasada and K. Yamada, "Calibration lines of HCN in the 1.5- μ m region," *Appl. Opt.* **29**, 3535 – 3547 (1990); S.L. Gilbert, W.C. Swann, and C.M. Wang, "Hydrogen cyanide $H^{13}C^{14}N$ absorption reference for 1530–1560 nm wavelength calibration – SRM 2519," *Natl. Inst. Std. Technol. Spec. Publ.* 260-137 (1998).
5. S. D. Dyer and K. B. Rochford, "Low-Coherence Interferometric Measurements of the Dispersion of Multiple Fiber Bragg-Gratings," *IEEE Photon. Technol. Lett.* **13**, 230 – 232 (2001).